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# The SILMU Scenarios: Specifying Finland's Future Climate for Use in Impact Assessment

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*Abstract*

*The development of climate change scenarios for Finland is described. These were required by researchers in the Finnish Research Programme on Climate Change (SILMU) for assessing the potential impacts of future climate change in Finland. The approach to scenario construction combines information from two sets of models: a simple model framework simulating greenhouse gas emissions, atmospheric composition, temperature and sea-level rise at global scale (MAGICC), and three coupled ocean atmosphere general circulation models (GCMs) simulating global and regional climate.*

*The scenarios are of surface temperature and precipitation for the period 1990-2100. Three policy-oriented scenarios have been developed: Central, Low and High. These attempt to embrace the range of uncertainty in projections. They are seasonal in resolution and apply to the whole of Finland. In addition, three scientific scenarios have also been developed, based on the regional and monthly pattern of change given by the GCMs.*

*Scenario climates can be defined for any location in the Nordic region and for any date up to 2100. Corresponding scenarios of* $CO_2$ *concentration and global mean sea-level rise are also presented. Furthermore, a stochastic weather generator is described that can be used to produce time series of daily data according to the scenario changes. Some features of the future climate not specified in the scenarios, such as other variables and changes in climatic variability are also discussed.*

*Key words: scenario, climate change, carbon dioxide, sea-level, Finland, weather generator*

## *1. Introduction*

### *1.1 Background*

The composition of the earth's atmosphere is changing. This is largely a result of human activities connected with industrialisation and should be of concern for two basic reasons. First, changes in certain constituents of the atmosphere can have a direct effect on processes occurring at the earth's surface. For example, increasing carbon dioxide concentrations can affect plant photosynthesis and water use; increasing sulphur dioxide concentrations can lead to acidification of precipitation and surface

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waters. Second, changes in trace gas and aerosol concentrations affect the radiative balance of the earth and hence the global climate. Since many natural systems and human activities are sensitive to climate, this is an important indirect effect of changing atmospheric composition.

In order to inform policy makers of the likely future changes in climate and their potential impacts, estimates are required of the future state of the atmosphere. These estimates are conventionally obtained through the use of numerical models. However, since current understanding of atmospheric processes is incomplete, model estimates are highly uncertain. A sequence of uncertainties can be identified, relating to: (i) future emissions of greenhouse gases and aerosols into the atmosphere, (ii) future atmospheric composition, (iii) the global climate response to changing atmospheric composition, and (iv) climate changes at regional and seasonal level. These uncertainties are cumulative and it is at the regional level, where the uncertainty is greatest, that information is most needed in impact assessments.

This paper addresses the problem of how to specify the future climate over one region of northern Europe: Finland. Projections were required for the Finnish Research Programme on Climate Change (SILMU) to serve a diversity of needs among scientists assessing the impacts of climate change in Finland. Since firm predictions were not available, the approach adopted involved the development of *climatic scenarios.*

### *1.2 Climatic scenarios*

Climatic scenarios are internally consistent and detailed specifications over space and time of plausible future climatic conditions. Scenarios are not predictions, since confident forecasts of future climate are not available. Rather, they are substitutes for predictions - research tools which can be used to explore the possible impacts of climate change. They should reflect our best estimates of the future climate, be consistent with projections of other related environmental variables, but at the same time embrace the likely uncertainties attached to these estimates.

### *1.3 Approaches to scenario development*

Several approaches have been used to develop regional climatic scenarios for climate change impact studies. These are reviewed in detail elsewhere (*Giorgi* and *Mearns,* 1991; *Pittock,* 1993; *Carter et al.,* 1994) and are summarised only briefly here. Not all approaches have been based on numerical climate model outputs, though most are developed with model estimates in mind. Climatic scenarios fall into four main classes: synthetic scenarios, analogue scenarios, scenarios from general circulation models, and composite scenarios.

*Synthetic scenarios* describe changes to observed time series of climatic data by realistic but arbitrary amounts (often according to a qualitative interpretation of model estimates for a region). For example, observed mean daily temperatures during one year at a site might be altered, successively, by increments of +1, +2, +3 and +4°C to simulate a warming of the climate. Although, given their arbitrary nature, these are not scenarios in the strict sense, they do offer useful tools for conducting sensitivity analyses in impact assessments.

*Analogue scenarios* are constructed by identifying recorded climatic regimes that may serve as analogues for the future climate in a given region. These records can be obtained either from the past (temporal analogues) or from another region at the present (spatial analogues). This approach has commonly involved the identification of periods or regions with a warmer climate than that prevailing in the study region today. However, the physical mechanisms and boundary conditions giving rise to warmer conditions in the past were almost certainly different from those involved in greenhouse gas induced climate change. Furthermore, regions with a plausible analogue climate today may not share other characteristics of a study region (e.g., soils, daylength, economic development). For these reasons, the use of analogue scenarios to represent future climate is not generally recommended (*IPCC*, 1990, p. xxv), although there may be certain applications where they can be used in conjunction with physically-based simulations.

*Scenarios from general circulation models (GCMs)* refer to estimates from physically-based three dimensional numerical models of the global climate system (*Gates et al.*, 1992). This is the only credible method currently available for simulating regional climate change, which is the information required in impact analysis. However, current estimates are highly uncertain due to, *inter alia*: 1) poor model representation of cloud processes, 2) too coarse spatial resolution (at best employing grid cells of some 250 km horizontal dimension), and 3) a simplified representation of land-atmosphere and ocean-atmosphere interactions and feedbacks. Recent advances in GCM development have included the coupling of dynamic ocean models to atmospheric models (*Gates et al.*, 1992) and the simultaneous modelling of aerosol and greenhouse gas effects on climate (*Taylor* and *Penner*, 1994; *Mitchell et al.*, 1995; *Cubasch et al.*, this volume).

*Composite scenarios* embrace a range of methods of combining some of the above techniques of scenario construction. Some workers have subjectively composited knowledge about past trends in climate, palaeoclimatic patterns and information from GCMs (*Pittock* and *Salinger*, 1982). Others have adopted a more quantitative approach such as averaging the outputs from different GCMs (*Santer et al.*, 1990). In order to address the need for regional scenarios, new techniques of downscaling from GCM outputs to sub-grid-scale are also under development, using various statistical methods (*Bardossy* and *Plate*, 1992; *Karl et al.*, 1990; *Wigley et al.*, 1990) or a nested modelling approach (*Giorgi et al.*, 1992; *Jones et al.*, 1995).

### *1.4 The needs of SILMU*

All researchers involved in climate impact assessment need to use some kind of climatic scenario. However, the needs vary widely according to the type of study being undertaken. The needs of researchers in SILMU were surveyed early in the programme, and are summarised in Table 1. To illustrate, some studies involved experiments conducted in controlled environments such as greenhouses and open top chambers to study plant responses to changes in climate and atmospheric composition. These studies required simple scenarios that represent a realistic combination of conditions in Finland at some time in the future (e.g., mean annual temperature change and $CO_2$ concentration at around 2100). In contrast, other studies employed mathematical models to simulate climate change impacts (for example, on hydrological systems, forest growth, energy production, crop yield). These studies often demanded information on future climate at a very high spatial (e.g., at sites) or temporal (e.g., daily) resolution.

Table 1. Information requirements for impact assessments in SILMU based on a survey of projects.

| Type of information | Requirement |
|---|---|
| *Spatial resolution:* | Finland at 10 km grid resolution (all)<br>Nordic with Baltic/North Sea (mar.)<br>Europe (agr.) |
| *Temporal resolution:* | Annual (hum.)<br>Monthly (agr., mar.)<br>Daily (all)<br>1-3 hourly (atm., for., wat.) |
| *Surface climatic variables (all):* | $CO_2$ concentration<br>Air temperature<br>Precipitation total<br>Global radiation<br>Humidity<br>Windspeed<br>Potential evaporation* |
| *Surface climatic variables (specific projects):* | $O_3$, $N_2O$, $SO_2$ concentrations (agr., atm., for.)<br>Cloudiness (atm., for.)<br>Direct/diffuse radiation (agr., atm., for.)<br>Net radiation (atm., for.)<br>Long wave radiation (atm., for.)<br>Atmospheric transmission (atm., for.)<br>Surface albedo (atm., for.)<br>Precipitation intensity (wat.)<br>Precipitable water (atm.)<br>Snow depth and duration (agr., wat.)<br>Runoff (mar., wat.)* |
| Upper air climatic variables (atm.): | Tropospheric aerosol content<br>Tropospheric/stratospheric ozone concentration<br>Cloudiness<br>Stratospheric temperature and circulation |
| Other variables: | Land use (all)<br>Sea level (mar., wat.) |

Abbreviations of research areas: agr. (agriculture), atm. (atmosphere), for. (forestry), hum. (human interactions), mar. (marine science), wat. (inland waters), all (all or most projects)

* Derived variables

Climatic scenarios have been employed in a few previous impact studies in Finland (*Kettunen et al.*, 1988; *Aittoniemi*, 1992), but these scenarios have become dated and are anyway limited in scope. In order to obtain expert opinion on the most appropriate methods of providing scenarios for this diversity of needs, SILMU arranged an International Workshop in 1993 on "Techniques for Developing Regional Climatic Scenarios". The recommendations of this meeting included the following (*Carter et al.*, 1993):

(1) Climatic scenarios should be based on the most recent results of simulations with general circulation models, especially those with coupled ocean-atmosphere models.

(2) Several scenarios should be selected to reflect the range of uncertainty in model estimates.

(3) Only existing and readily accessible methods of scenario development should be considered within the time frame of SILMU.

(4) All scenarios should be developed relative to a consistent baseline: 1990 for atmospheric composition and 1961-1990 for the observed climatology.

(5) Scenarios should be specified for at least three time slices in the future (e.g., 2020, 2050 and 2100).

(6) Scenarios should be developed at three spatial and temporal scales:

- Generalised scenarios of seasonal or annual changes over the entire Nordic region, comprising a central estimate and upper and lower limits of uncertainty.
- Regional scenarios for Finland, at a monthly and 10 x 10 km grid resolution.
- Local scenarios for individual sites at a daily resolution.

The scenarios were developed during 1994 and provided to SILMU researchers in the form of a computer program and User's Guide (*Carter et al.*, 1995). The following sections describe in more detail the approach adopted to develop these scenarios.

## 2. *Approach*

The approach adopted for scenario development is a refinement of a composite method developed at the University of East Anglia, UK (*Viner* and *Hulme*, 1993). Variants of the method have been used to construct scenarios for various research projects (e.g., *Hulme et al.*, 1995a; *Harrison et al.*, 1995) as well as for climate impact researchers involved in Working Group II of the Intergovernmental Panel on Climate Change (IPCC), providing a consistent framework for reviewing the potential impacts of climate change (*TSU*, 1994).

The approach makes use of information from two sets of models (Fig. 1): (i) MAGICC, a framework of simple global models for estimating changes in radiative forcing under different emissions scenarios and its effect on global mean temperatures and sea level, and (ii) general circulation models, which provide estimates of the large scale pattern of climate changes under given radiative forcings.

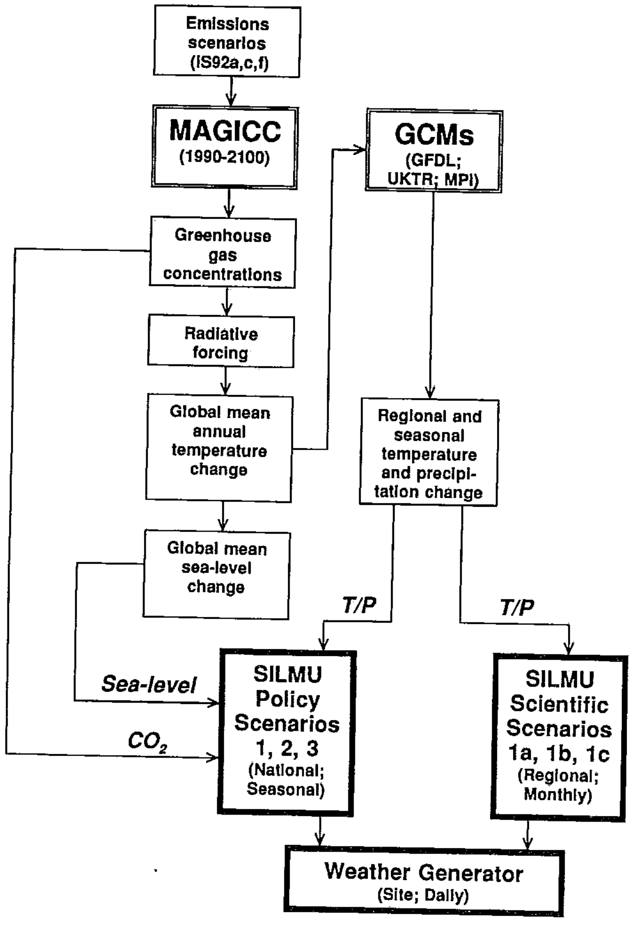


Fig. 1. Approach to scenario development (schematic).

## 2.1 *Global projections from MAGICC*

The Model for the Assessment of Greenhouse-gas Impacts and Climate Change (MAGICC) is a set of coupled gas-cycle, climate and ice-melt models designed to study the effectiveness of policies to control emissions into the atmosphere, and to determine the sensitivity of results to plausible model parameter changes (*Hulme et al.*, 1995b). It includes all the major greenhouse gases (except tropospheric ozone), fossil fuel derived

$SO_2$ emissions and their effects on climate as aerosols, and the effect of halocarbon-induced stratospheric ozone depletion.

MAGICC is made up of the following components: (i) a carbon cycle model (*Wigley,* 1993) for computing $CO_2$ concentrations; (ii) simple mass balance models for computing concentrations of methane (*Osborn* and *Wigley,* 1994), $N_2O$ and halocarbons; (iii) a sulphate aerosol model for $SO_2$ emissions from fossil sources (*Wigley* and *Raper,* 1992); (iv) various schemes for converting gas and aerosol concentrations to radiative forcing; (v) an upwelling-diffusion, energy balance model to compute global mean annual temperature and the oceanic thermal expansion component of global mean sea-level rise (*Wigley* and *Raper,* 1992; 1993); and (vi) ice melt models for "small" glaciers and the Greenland and Antarctic ice sheets (*Wigley* and *Raper,* 1993). These component models, although simple, nevertheless produce results that are close to those obtained from more complex, state-of-the-art models. Further details can be found in the MAGICC Reference Manual (*Wigley,* 1994).

The primary inputs to MAGICC are emissions scenarios at decadal intervals between 1990 and 2100 for the following: fossil $CO_2$, net land-use-change $CO_2$, $CH_4$, $N_2O$, CO, $NO_x$, VOCs, CFC11, CFC12, HCFC22, HFC134a and $SO_2$ (*Wigley,* 1994). Emissions scenarios can be selected from a list of published scenarios or can be user-specified. The models calculate the radiative forcing due to emissions over the period 1765-2100, the global mean annual temperature response to a given forcing and the global mean sea-level effect of the temperature change. Model parameter uncertainties are also represented in model outputs.

A version of MAGICC dating from May 1993 was made available for the SILMU work (*T. Wigley,* pers. comm., 1993). This differs little from more recent, updated versions. MAGICC was used to estimate two major uncertainties arising from first, the range of possible future emissions, and second, the range of climate responses to a given radiative forcing (climate sensitivity).

The range of emissions is based on the IPCC scenarios developed in 1992 and subsequently endorsed in 1994 (*IPCC,* 1992; 1995). The IS92f scenario was selected as the high emissions scenario. Although the emissions are lower in this scenario than in the IS92e scenario, the estimated global temperature response in MAGICC is greater for IS92f than IS92e if negative forcing from sulphate aerosols and stratospheric ozone feedback effects are computed. The IS92c scenario was chosen as the low emissions scenario, and a "central" estimate scenario, IS92a, was adopted in common with IPCC practice.

The climate sensitivity is defined as the global mean temperature change for an increase in greenhouse gas concentrations equivalent to a doubling of carbon dioxide. Values of the climate sensitivity have been obtained using general circulation models. The range adopted here was 1.5-4.5°C, with a central estimate of 2.5°C, again following IPCC recommendations (*IPCC,* 1992).

Three combinations of these global scenarios, representing the central "best guess" scenarios and an extreme range were adopted for SILMU:

- Scenario 1: Central - central emissions/central sensitivity (IS92a/2.5°C)
- Scenario 2: Low - low emissions/low sensitivity (IS92c/1.5°C)
- Scenario 3: High - high emissions/high sensitivity (IS92f/4.5°C).

MAGICC was run with these combinations, also simulating the global effects of sulphate aerosol forcing, to give a range of $CO_2$ concentrations (Fig. 2), global mean annual temperature change estimates (Fig. 3) and sea-level rise estimates (Fig. 4) for the period 1990-2100. The global temperature scenarios form the basis for construction of regional climatic scenarios.

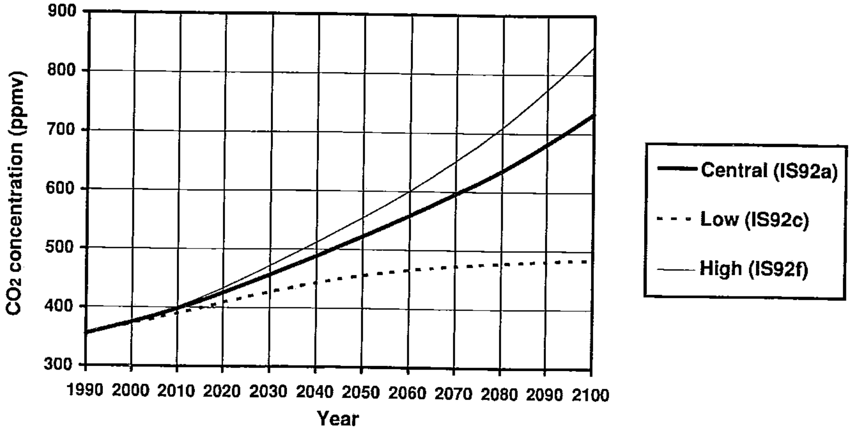


Fig. 2. Atmospheric carbon dioxide concentration estimated by MAGICC under the IS92c, IS92a and IS92f emissions scenarios.

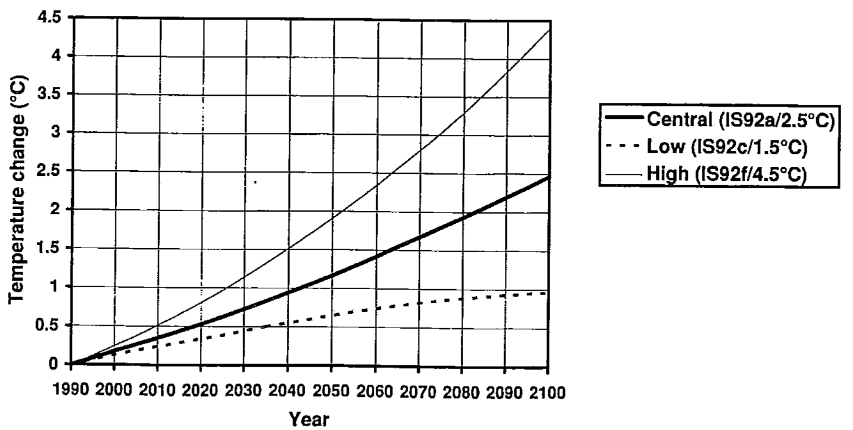


Fig. 3. Global mean annual temperature change estimated by MAGICC for: IS92c emissions and a climate sensitivity of 1.5°C (lower curve), IS92a emissions/2.5°C sensitivity (middle curve) and IS92f emissions/4.5°C sensitivity (upper curve).

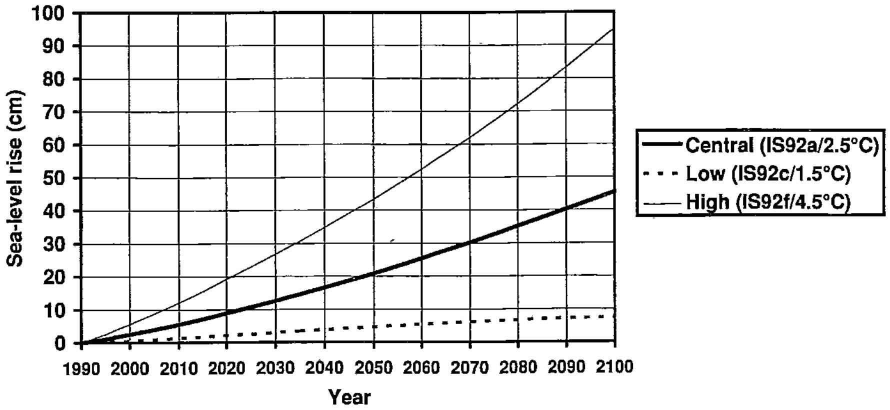


Fig. 4. Global mean sea-level rise for the temperature scenarios given in Figure 3.

## 2.2 *Regional projections from GCMs*

The regional scenarios are based on outputs from three general circulation models: the Geophysical Fluid Dynamics Laboratory (GFDL) model from Princeton, USA (*Manabe et al.,* 1991), the United Kingdom Meteorological Office transient (UKTR) model from the Hadley Centre, Bracknell, UK (*Murphy,* 1995) and the Max Planck Institut für Meteorologie (MPI) model from Hamburg, Germany (also referred to as the ECHAM-1 model - *Cubasch et al.,* 1992). All three are coupled ocean-atmosphere models and all three have been used to simulate the transient response of climate to a gradual increase in atmospheric greenhouse gas concentrations for varying periods into the future. More details about the models are given in Table 2. Data from the models were supplied by the Climate Impacts LINK Project at the University of East Anglia, UK (*D. Viner,* pers. comm., 1994).

The models represent the state of knowledge in the early 1990s. As such, the regional pattern of climate change simulated with these models was for greenhouse gas forcing only, and did not account for sulphate aerosols. An intercomparison of their performance (along with four other GCMs) in reproducing the present-day climate over the Nordic region in control simulations where greenhouse gas concentrations were fixed was undertaken by *Räisänen* (1994). Direct comparisons were reported for two variables: sea-level pressure and surface air temperature, with the following conclusions:

(1) Of the three GCMs used here, the GFDL model gives the most realistic mean winter sea-level pressure distribution in northern Europe, followed by the UKTR and MPI models. Performance in summer is mixed, and it is more difficult to rank the models.

(2) All three models underestimate surface air temperatures over northern Europe in winter, though the GFDL simulations are the most realistic. In summer the temperature biases are less and vary in sign, but over Finland all three models give too low values.

Table 2. Some characteristics of the three GCMs.

| Model features | GFDL | UKTR | MPI (ECHAM1) |
|---|---|---|---|
| **Atmosphere:** | | | |
| Latitude/longitude resolution | 4.5° x 7.5° | 2.5° x 3.75° | 5.63° x 5.63° |
| Grid box size at 60°N | 500 x 415 km | 250 x 210 km | 625 x 310 km |
| No. horizontal grid boxes: | | | |
| Global | 1920 | 6912 | 2048 |
| Finland | 6 | 15 | 6 |
| Vertical layers | 9 | 11 | 19 |
| **Ocean:** | | | |
| Latitude/longitude resolution | 4.5° x 3.75° | 2.5 x 3.75 | 4.0° x 4.0° |
| Grid box size at 60°N | 500 x 210 km | 250 x 210 km | 445 x 220 km |
| Vertical layers | 12 | 17 | 11 |
| **Increase in greenhouse gas concentration assumed** | 1%/year equivalent $CO_2$ (compound) | 1%/year equivalent $CO_2$ (compound) | IPCC scenario A for equivalent $CO_2$ |

GFDL Geophysical Fluid Dynamics Laboratory, Princeton, USA (*Manabe et al.*, 1991).
UKTR United Kingdom Meteorological Office, Bracknell, UK Transient run (*Murphy*, 1995).
MPI (ECHAM1) Max Planck Institute for Meteorology, Hamburg, Germany (*Cubasch et al.*, 1992).

In view of the deficiencies in the control simulations highlighted by the intercomparison exercise, it is important to recognise an implicit assumption made here (and elsewhere) in developing scenarios: that any errors in the climate change simulation are likely to be similar in character to those of the control simulation. Following this logic, the most common approach involves taking the difference or ratio between outputs from the two simulations as indicative of the anticipated change in climate relative to the present. If this assumption is not valid (and there is no prior way of testing it), then the value of GCM outputs for impact assessment is called into question.

There were two additional problems in applying these GCM results for scenario development. First, the modelled climate response to future increases in greenhouse gas concentrations was simulated beginning from a period representing the present-day. Simulations neglected to account for the increases in concentrations that have already occurred since pre-industrial times, so the simulated response is unrealistically small in the first few decades - the so-called "cold start" problem (*Hasselmann et al.*, 1993). In practice, this meant that the simulated years could not be interpreted as real calendar years.

A second problem relates to model "drift". This is the tendency for the modelled global mean temperatures gradually to deviate over time from a stable equilibrium, probably due to a too short time taken in bringing the coupled models to equilibrium or due to some small errors in the coupling of ocean and atmosphere models which become exaggerated over time.

The methods used to address these problems are described in the following section.

## 3. *Construction of temperature and precipitation change scenarios*

Two types of climatic scenario have been distinguished for SILMU: policy-oriented scenarios and scientific scenarios. Corresponding to each of these climatic scenarios are scenarios of $CO_2$ concentration and sea-level rise. Possible changes in other variables are discussed in the next section.

### 3.1 *SILMU policy-oriented scenarios*

The SILMU policy oriented scenarios attempt to capture the range of uncertainty in estimating future climate over Finland. At the same time, they are designed to be simple for scientists to apply and for policy makers to interpret. They depict seasonal changes and are uniform over the whole country. Three "policy scenarios" have been developed:

- SILMU Scenario 1: Central
- SILMU Scenario 2: Low
- SILMU Scenario 3: High

These are based on combining results at global level obtained from MAGICC (shown above) with regional scale climate change estimates from the three GCMs. To obtain estimates of temperature and precipitation change for Finland the following procedure was used:

(1) The global mean annual temperature change for 1990-2100 was estimated with MAGICC for each of the three scenario combinations and the levels of change were noted for the years 2020, 2050 and 2100 (cf. Fig. 2). The calculations also accounted for the cooling effect of sulphate aerosols, but only at a global scale.

(2) Plots of global mean annual temperature change were constructed for the three GCM simulations. The effects of model drift (see above) were removed by subtracting decadal running means of the control simulations from running means for corresponding decades of the climate change simulations. All three GCM simulations exhibit a long-term warming trend relative to their respective control simulations (Fig. 5).

(3) The modelled years in which 10-year running means of the climate warming estimated by the GCMs reached the same level as that obtained from MAGICC for 2020, 2050 and 2100 were extracted for each model. This was a method of circumventing the cold start problem by using MAGICC to estimate the rate of global warming. The years obtained are shown in Table 3. In all models the warming exceeded that obtained by 2050 with MAGICC. However, only the GFDL model could be used directly to provide estimates for 2100.

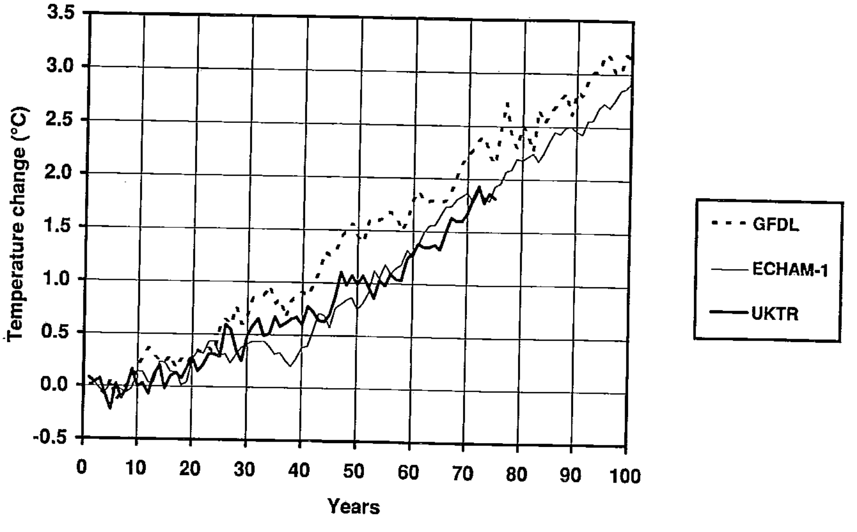


Fig. 5. Global mean annual temperature change estimated by the three GCMs.

Table 3. Model years in the three GCM simulations in which global mean annual warming corresponds to that estimated by MAGICC for 2020, 2050 and 2100 (assuming IS92a emissions and 2.5°C climate sensitivity).

| Year | Global mean annual warming from MAGICC (°C) | Model year in which warming attained | | |
|---|---|---|---|---|
| | | GFDL | UKTR | MPI (ECHAM1) |
| **2020** | 0.53 | 25 | 32 | 42 |
| **2050** | 1.16 | 44 | 58 | 56 |
| **2100** | 2.47 | 80 | - | - |

(4) In order to obtain statistics about the climate at the times shown in Table 3, a period of modelled years was extracted around each year. Seasonal mean temperature and precipitation changes for the Finnish region were obtained from each GCM as the areally weighted mean of the GCM grid box values over the region (cf. Table 2). These results were simplified into linear trends in temperature and precipitation from 1990-2100, extrapolating to 2100 where necessary, and then averaged into composites. The precipitation change estimates for Scenarios 2 and 3 are scaled up or down from Scenario 1 estimates in proportion to the respective temperature changes. In this way, upper, lower and central estimates of the rate of temperature and precipitation change are given for Finland (Table 4).

Table 4. The SILMU Policy Scenarios, 1990-2100.

| | **Temperature change (°C/decade)** | | | **Precipitation change (%/decade)*** | | |
|---|---|---|---|---|---|---|
| **Period** | **1 (Central)** | **2 (Low)** | **3 (High)** | **1 (Central)** | **2 (Low)** | **3 (High)** |
| **Spring (MAM)** | 0.4 | 0.1 | 0.6 | 0.5 | 0.125 | 0.75 |
| **Summer (JJA)** | 0.3 | 0.075 | 0.45 | 1.0 | 0.25 | 1.5 |
| **Autumn (SON)** | 0.4 | 0.1 | 0.6 | 1.0 | 0.25 | 1.5 |
| **Winter (DJF)** | 0.6 | 0.125 | 0.75 | 2.0 | 0.42 | 2.5 |
| **Annual** | 0.4 | 0.1 | 0.6 | 1.0 | 0.25 | 1.5 |

* Rates of precipitation change are averages. A wide range of uncertainty accompanies each value.

This compositing procedure can be justified for temperatures, given the surprisingly close agreement between estimates of temperature change from the three GCMs. However, there is considerable variation (in magnitude and even in sign) between the GCM estimates of precipitation change. The values given in Table 4, which are averages, should therefore be treated with caution.

Scenarios of $CO_2$ concentration and mean sea-level rise that are consistent with the regional climatic scenarios given in Table 4 can be obtained from MAGICC (cf. Figures 2 and 4). These are useful for impact assessment and are illustrated alongside the climate changes in Table 5 for the years 2020, 2050 and 2100.

Table 5. Carbon dioxide concentration (absolute), regional mean annual temperature and precipitation change and global mean sea-level rise (relative to 1990) for 2020, 2050 and 2100 under the three SILMU policy scenarios.

| | **SILMU Policy Scenarios** | | |
|---|---|---|---|
| **Year and attribute** | **1 (Central** | **2 (Low)** | **3 (High)** |
| **2020** | | | |
| $CO_2$ concentration (ppmv) | 425.6 | 408.8 | 433.7 |
| Temperature change (°C) | 1.2 | 0.3 | 1.8 |
| Precipitation change (%) | 3.0 | 0.75 | 4.5 |
| Sea-level rise (cm) | 8.9 | 2.1 | 19.2 |
| **2050** | | | |
| $CO_2$ concentration (ppmv) | 523.0 | 456.1 | 554.8 |
| Temperature change (°C) | 2.4 | 0.6 | 3.6 |
| Precipitation change (%) | 6.0 | 1.5 | 9.0 |
| Sea-level rise (cm) | 20.8 | 4.6 | 43.3 |
| **2100** | | | |
| $CO_2$ concentration (ppmv) | 733.3 | 484.9 | 848.2 |
| Temperature change (°C) | 4.4 | 1.1 | 6.6 |
| Precipitation change (%) | 11.0 | 2.75 | 16.5 |
| Sea-level rise (cm) | 45.4 | 7.4 | 95.0 |

### 3.2 *The SILMU Scientific Scenarios*

The SILMU scientific scenarios refer to scenarios that are derived directly from GCM outputs. They provide spatial and temporal variations that the policy scenarios do not. Three scientific scenarios have been developed, based on the three GCMs, and with the same emissions and climate sensitivity assumptions as policy Scenario 1:

- SILMU Scenario 1a: GFDL
- SILMU Scenario 1b: UKTR
- SILMU Scenario 1c: MPI

The scenarios are based on the pattern of climate change over the Nordic region simulated by each GCM at the times when the global mean annual temperature change was the same as that simulated by MAGICC for 2020 and 2050. Only the GFDL model provided estimates for 2100. Estimates for the MPI model extend to 2081 and for the UKTR model, to 2050. Full time series of gridded data were available from the GFDL and UKTR models, but only three 10-year time windows were available from the MPI model, representing time slices slightly different from those selected in Table 3.

One important point to note in analysing the GCM outputs is the large amount of inter-decadal variability in the time series of both temperature and precipitation. This was studied for the GFDL and UKTR models by plotting ten-year and thirty-year running mean values of the control simulations, climate change simulations and the change between them averaged over Finland. An example for temperature change is shown in Figure 6. It has been common practice among climate modellers to extract decadal periods from model runs for deriving climatic statistics and for developing scenarios. However, this procedure is clearly inadvisable, as the resulting climate change fields obtained for a given time window may be unrepresentative of the long-term trends. For instance, selection of the decadal windows centred at years 20 and 60 in Figure 6 would indicate a cooling between these dates, whereas the long-term trend is clearly positive. For this reason, the time windows selected for the GFDL and UKTR models were all 30-year periods centred around a given year. Only decadal periods were available from the MPI outputs.

Gridded monthly mean climate change fields from each model (differences in °C for temperatures and percentage changes for precipitation) were computed for the periods described above. In order to allow SILMU researchers to specify monthly temperature and precipitation changes for any point in the Nordic region and for any year from 1990-2100, routines were included in the computer program that linearly interpolate from the gridded time windows. Alternatively, scenarios can be depicted over a finer-scale 1° by 2° latitude-longitude grid covering the Baltic region, or a 10 x 10 km grid over Finland.

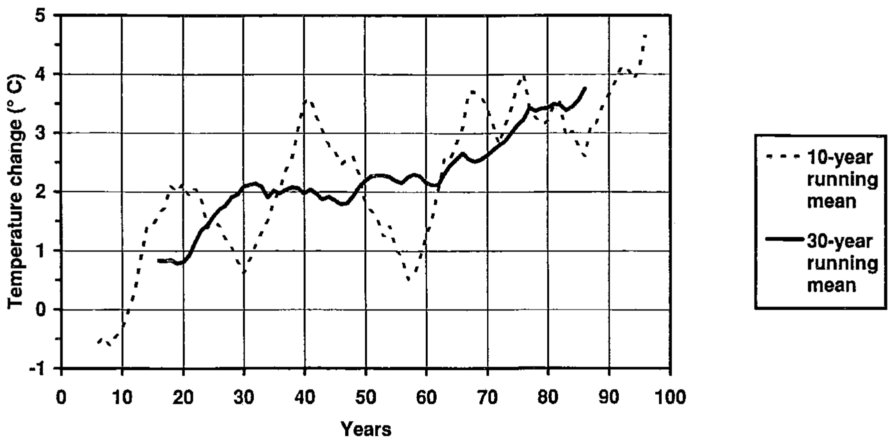


Fig. 6. Comparison of ten-year and thirty-year running means of the change (°C) between the GFDL control and climate change simulations of spring (MAM) temperature. Values are averages of six grid boxes over Finland.

Linear interpolation was employed in the spatial downscaling in preference to more sophisticated methods (see Section 1.3, above) due to time constraints. Use of original GCM grid box values for specifying regional scenarios was rejected, since sharp differences can sometimes be found between adjacent grid box values rather than the smooth climate change fields that are required in regional-scale impact studies. Use of linear interpolation between the time windows can be justified by the near linear rise in mean temperatures in all three simulations (cf. Fig. 5), though the form of long-term precipitation trends is more difficult to assess. The net effect of the interpolation procedures is to create a smoothed pattern of climate change that evolves from one time window to the next. Figure 7 illustrates this evolution interpolated to Finland for outputs from two models (GFDL and UKTR) of mean June temperature change by 2020 and 2050.

## 4. *Other climate changes*

The SILMU scenarios only consider mean changes in temperature and precipitation explicitly. However, changes in other aspects of the future climate may also be of importance for impact assessment. Some of these possible changes are described here, based on information from the literature and from recent unpublished work. Even if the information cannot be used directly as scenarios, it may be useful for conducting sensitivity studies.

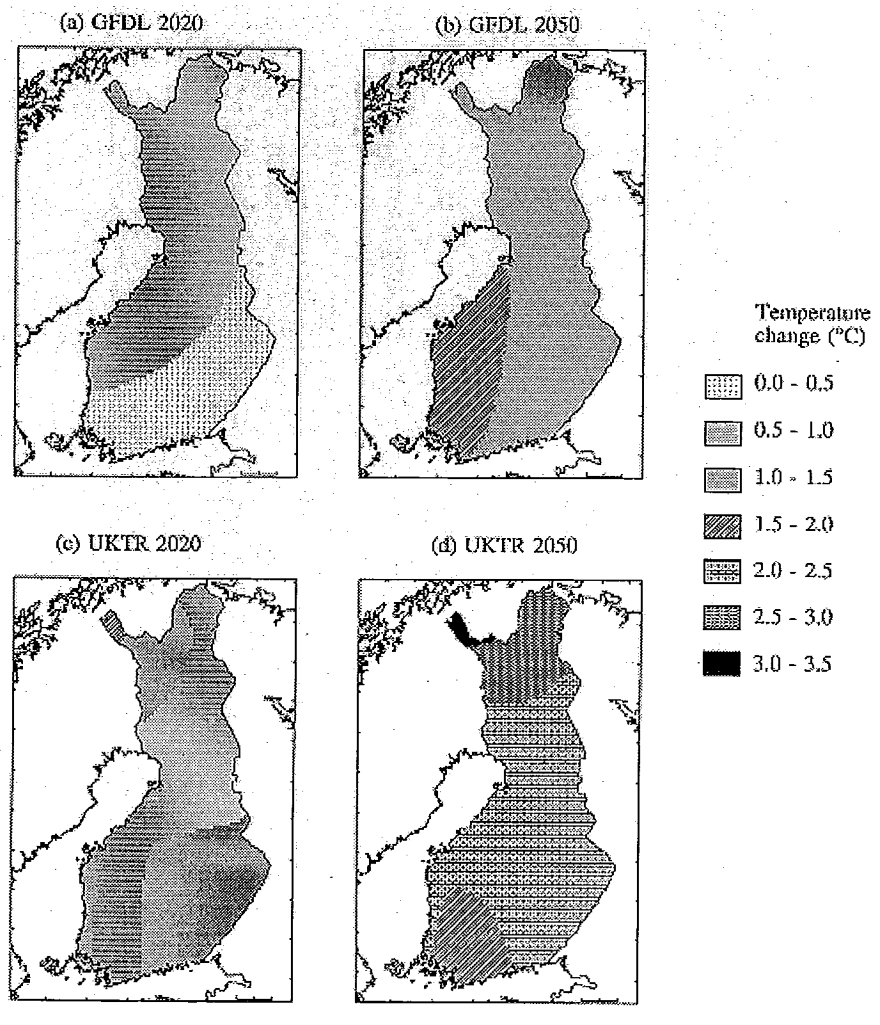


Fig. 7. Mean June temperature change by 2020 and 2050 over Finland for SILMU scenarios 1a (a and b) and 1b (c and d) based on interpolated outputs from the GFDL and UKTR models, respectively.

### *4.1 Temperature and precipitation variability*

The inter-annual variability of seasonal temperature and precipitation was analysed for the three GCM simulations described above. The only results to show statistically significant changes were from the GFDL model, where the standard deviations of spring, summer and annual precipitation increased by about 50% between 1990 and 2100 (significant at the 95% level; chi-squared test). No comparable trends were detected in the shorter UKTR and MPI simulations.

### 4.2 *Precipitation frequency and intensity*

Changes in the frequency distribution of precipitation can be as important as changes in the mean in assessing some impacts. These have been studied for modelled daily precipitation from equilibrium 2 x $CO_2$ simulations with the Commonwealth Scientific and Industrial Research Organisation nine layer model (CSIRO9) (*McGregor et al.,* 1993) and the UK Meteorological Office High Resolution model (UKHI) (*Gregory* and *Mitchell,* 1995).

Results over the Finnish region indicate that while precipitation increases in most months (in line with the SILMU scenarios), these increases are mainly associated with increased intensity of precipitation (*K. Hennessy* and *A. Fowler,* pers. comm., 1994). The return period of heavy rainfall events decreases markedly. The increased intensity appears to be attributable both to local scale activity as well as to large scale processes (i.e., fronts associated with storm tracks). This points to increased convection, due to higher temperatures, but also to increased "storminess" (see below) as likely mechanisms for change (*Gregory* and *Mitchell,* 1995).

The results indicate that it may be reasonable, as a first approximation, to allocate changes in monthly precipitation evenly between the existing raindays, keeping the number of raindays unchanged. However, some of the model results also suggest that the number of dry days increases under climate warming (*Gregory* and *Mitchell,* 1995; *Gordon et al.,* 1992), which might also be a useful sensitivity test in impact studies.

### 4.3 *Diurnal temperature range*

During recent decades, observations have indicated a distinct narrowing of the diurnal temperature range in many regions of the world (*Karl et al.,* 1993). Between 1950 and 1990, the mean daily maximum air temperature over land areas increased by 0.28°C while the mean daily minimum increased by 0.84°C (*Hansen et al.,* 1995). In Finland, the mean maximum temperatures averaged across eight long-term stations increased by about 0.7°C during the period 1951-1993 whereas mean minima increased by 1.5°C (*Heino,* 1994).

The explanation for this phenomenon is thought to be a combination of observed increases in low-level cloudiness and aerosol optical depth and a large-scale warming factor such as greenhouse gas increases (*Harvey,* 1995). However, modelling studies suggest that this may be only a transient effect. Rapid increases in $CO_2$ (which directly affects the atmospheric infrared absorptivity), aerosol concentrations and cloudiness can explain the damping of the diurnal temperature range, while the greenhouse gas induced increase in mean temperature are delayed by several decades. As the climate comes into closer balance with the radiative forcing, however, it has been suggested that the difference between the increase in maximum and minimum temperatures will shrink (*Hansen et al.,* 1995).

Thus, some further narrowing of the diurnal range may occur in the short-term, an effect that could be tested in impact studies by allocating a greater proportion of a scenario warming to the minimum than the maximum temperatures. However, the damping effect is not likely to be sustained for very long.

### 4.4 *The radiation climate*

Recent observed changes in cloudiness and aerosol loading, noted above, appear to have contributed to a decrease in incident solar radiation over Finland since the 1970s (*Heino,* 1994; *Heikinheimo* and *Venäläinen,* 1994). Monthly data on global radiation were available from the three GCMs used in constructing the SILMU scenarios, but for shorter, 10-year averaging periods. No clear changes in radiation are apparant except in winter, for which declines were recorded. These declines are mirrored by increasing winter cloudiness in all models at the time of equivalent $CO_2$ doubling. The impacts of these changes are likely to be minimal, however, given that global radiation totals in winter are small in Finland.

### 4.5 *Air humidity*

A warmer atmosphere is capable of holding more water vapour, and the relationship is non-linear: as air temperature rises, its saturation vapour pressure rises faster. A warmer atmosphere would also be expected to evaporate more water from the Earth's surface, thus increasing the specific humidity. On the other hand, model results indicate that the relative humidity (a measure of the relative "drying power" of the air) remains fairly constant in the warmer climate (*Gregory* and *Mitchell,* 1995).

### 4.6 *Storminess*

There is much current debate about probable changes in frequency and intensity of storm activity. With higher ocean temperatures there will be greater energy available for the initiation and propagation of cyclonic activity in the western Atlantic. This is the source area for many of the storms that occur in northwestern Europe. On the other hand, the north-south temperature gradient, which is also important for cyclone initiation, is consistently predicted by models to decrease at lower levels, though it may increase at upper levels (*J. Kaurola,* pers. comm., 1995). The implications of these changes for cyclone activity are not yet clear, and results from model simulations vary from model to model (*Hall et al.,* 1994; *Stephenson* and *Held,* 1993; *von Storch et al.,* 1993).

Any changes in the frequency or intensity of storms will obviously be expressed in observations of extreme windspeeds. However, average windspeeds are more closely related to mean surface pressure patterns and pressure gradients. In one of the few studies reported, windspeed changes for 2 x $CO_2$ climates simulated by three low resolution GCMs have been analysed for Europe, but gave contradictory results over Finland in all seasons (*Barrow,* 1993).

## *5. Discussion*

The main focus of this paper has been on scenario development, but at least as important is the correct application of these scenarios in impact assessment studies. Some aspects of this are described below, although scenario application is described in more detail elsewhere (*Carter et al.,* 1994; 1995). In addition, it is of interest to compare the SILMU scenarios with other climate projections for the Nordic region. Finally, some ideas are presented on how climatic scenarios might be refined for future applications.

### *5.1 Applying the SILMU scenarios*

The first consideration in applying any scenario of climate change in an impact study is to define the reference climate. In this case the observed climatology from the period 1961-1990 represents the climatological baseline for SILMU. This is the most recent standard "normal" period defined by the World Meteorological Organization. It was adopted to represent both the average recent climate and its variability, and can be described either as a 30-year mean or as a time series of data for all thirty years. The baseline climate may be for a site, a regional average, or gridded across the whole country. Since the SILMU scenarios, which are relative to 1990, are applied to the entire baseline period, this implies no significant climatic trends between 1961 and 1990. This is a reasonable assumption for mean annual temperature in Finland, although there is a strong positive trend in spring temperatures and a weaker positive trend in annual precipitation.

There are two basic methods of perturbing the baseline climate according to the scenario changes, termed here the "fixed change" approach and the "transient change" approach. The first of these is the conventional approach, inherited from scenarios developed for equilibrium climate changes. It takes a single set of scenario changes in climate for a date in the future (whether monthly, seasonal or annual) and adjusts the whole baseline period according to these changes. This has the effect of shifting the baseline climate (assumed to be stationary) to a new stationary state. The method is simple to apply, but it ignores the transient nature of climate change.

The second approach recognises that climate is changing continually, imposing the scenario adjustments as a transient change relative to the baseline climate. For example, the temperature in the period around 2050 can be represented in the SILMU scenarios by a trend from 2036-2065, with 1961 baseline temperatures adjusted according to the scenario for 2036, 1962 temperatures according to the 2037 scenario, and so on. This method, since it incorporates a trend, probably produces a more realistic future climate than the stationary case, and may give rise to slightly different impacts.

### 5.2 *Using a weather generator*

An alternative method from using obervational data in specifying the baseline and future climate is to use a stochastic weather generator. This can produce time series of climatological data having statistical characteristics in common with observational weather data in a region. A weather generator for daily precipitation, mean air temperature and cloudiness over Finland has been developed for SILMU (*Posch,* 1994; *Carter et al.,* 1995). The generator (CLIGEN) first simulates time series of daily precipitation, which is the independent variable in the procedure. Daily temperatures and cloudiness values are then computed using correlations with the occurrence of wet and dry days, based on the method of *Richardson* and *Wright* (1984). The parameters of the generator have been obtained for all stations providing data across Finland during 1961-1990. Interpolation procedures allow time series to be generated for any location in Finland.

CLIGEN has been developed in such a way that the parameter values of the generator can be adjusted to simulate climate changes according to the SILMU policy scenarios. Other advantages of this tool include the possibility to substitute large quantities of daily observational data with a few parameters describing their frequency distribution, and the ability to generate data time series of unlimited length.

Some drawbacks of weather generators of this kind include their failure to describe all aspects of the climate accurately, especially persistent events like drought and warm spells or some extreme events (*Racsko et al.*, 1991), and their dependence on historically derived correlations between climatic variables that may not be valid under a changed climate.

### 5.3 *Other climate change projections for the Nordic region*

The SILMU scenarios are not the only climate projections available for the Finnish region, and it is interesting to compare them with information from more recent climate model simulations as well as with scenarios developed by other researchers.

The major recent advance in climate modelling has been the addition of regional sulphate aerosol forcing in climate change model simulations (*Taylor* and *Penner,* 1994; *Mitchell et al.,* 1995; *Cubasch et al.,* this volume). The latter two simulations were with coupled ocean-atmosphere models (from the UK Hadley Centre and Max Planck Institute, respectively) and were run from dates late in the last century through to 2050, thus overcoming the "cold start" problem. For the first time, the modelled global mean warming is similar in magnitude to that observed for the period up to present. Both models predict a similar rate of global mean annual warming, of about

0.2°C per decade with sulphate aerosols included. This compares with 0.3°C per decade for greenhouse gases alone.

Although the SILMU scenarios account for the cooling effect of sulphates at a global level, using MAGICC, the regional pattern of climate change inferred from the three GCMs is for a greenhouse forcing alone. These more recent simulations, however, offer a representation of the regional responses to forcing from both aerosols and greenhouse gases. Approximate rates of annual mean temperature change up to 2050 over the Nordic countries have been inferred from the mapped results of the Hadley Centre simulations (*Mitchell et al.,* 1995) and are compared with scenarios for each country using the SILMU method in Table 6.

Table 6. Some recent estimates of future temperature change in the Nordic countries (°C/decade).

| Country | | SILMU method[1] | Nordic expert group[2] | Hadley Centre (sulphates)[3] |
|---|---|---|---|---|
| **Denmark** | Annual (range) | **0.35 (0.10-0.50)** | **0.35** | **0.35** |
| | Summer/Winter | 0.20/0.50 | 0.25/0.45 | - |
| **Finland** | Annual (range) | **0.40 (0.10-0.60)** | **0.45** | **0.45** |
| | Summer Winter | 0.30/0.60 | 0.30/0.60 | - |
| **Iceland** | Annual (range) | **0.15 (0.05-0.25)** | **0.30** | **0.30** |
| | Summer/Winter | 0.15/0.15 | 0.25/0.35 | - |
| **Norway** | Annual (range) | **0.35 (0.10-0.50)** | **0.40** | **0.40** |
| | Summer/Winter | 0.25/0.50 | 0.25/0.55 | - |
| **Sweden** | Annual (range) | **0.35 (0.10-0.55)** | **0.40** | **0.40** |
| | Summer/Winter | 0.30/0.50 | 0.25/0.55 | - |

1. This paper
2. *Johannesson et al.* (1995)
3. *Mitchell et al.* (1995)

Also compared in Table 6 is a temperature scenario developed for the Nordic region in a study of climate change and energy production (*Johannesson et al.,* 1995). The scenario is based on expert judgement by meteorologists in the project and was developed before the sulphate aerosol simulations were reported. Temperature and precipitation scenarios were provided as maps, but uncertainties in projections were not quantified. The changes in temperature are consistent with the central SILMU estimates in all countries except Iceland (Table 6). Interestingly, though coincidentally, the experts' estimates are also identical to the Hadley Centre results.

### 5.4 *Further developments*

Climate modelling and prediction is evolving rapidly, as knowledge of the basic processes improves and computing power increases. Detailed results from the sulphate aerosol simulations described above are now available for analysis. One promising approach for producing finer scale regional scenarios is the use of high resolution regional climate models nested in a GCM. Preliminary results from these models are already being reported for Europe (*Giorgi et al.*, 1992; *Jones et al.*, 1995) and are also available for impact assessment. The next few years will probably witness the gradual incorporation of various chemical processes in the atmosphere thought to be responsible for the formation and breakdown of atmospheric constituents affecting global climate. The concentrations and effects of individual greenhouse gases will be treated separately rather than aggregated, and stratospheric ozone depletion may also be included in the model experiments. Equally important, is an improved representation of surface processes and feedbacks and of the ocean circulation.

Each of these developments should assist in narrowing the range of uncertainty that characterises the SILMU scenarios.

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*References*

Aittoniemi, P., 1992. Influences of climate change on the Finnish energy economy. In: Østren, G. (Ed.), *Nordisk Hydrologisk Konferanse* 1992. Alta, Norway, pp. 75-84.

Bardossy, A., and E.J. Plate, 1992. Space-time model for daily rainfall using atmospheric circulation patterns. *Water Resour. Res.*, **28**, 1247-1259.

Barrow, E.M., 1993. Scenarios of climate change for the European Community. *Eur. J. Agron.*, **2(4)**, 247-260.

Carter, T., E. Holopainen, and M. Kanninen (Eds), 1993. Techniques for developing regional climatic scenarios for Finland. *Publications of the Academy of Finland 2/93*, Helsinki, 63 pp.

Carter, T.R., M.L. Parry, H. Harasawa, and S. Nishioka, 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Intergovernmental Panel on Climate Change. Department of Geography, University College London, UK and Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 59 pp.

Carter, T., M. Posch, and H. Tuomenvirta, 1995. SILMUSCEN and CLIGEN user's guide: Guidelines for the construction of climatic scenarios and use of a stochastic weather generator in the Finnish Research Programme on Climate Change (SILMU). *Publications of the Academy of Finland 5/95*, Helsinki. 60 pp. plus diskette.

Cubasch, U., K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer, and R. Sausen, 1992. Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Clim. Dyn.*, **7**, 55-69.

Gates, W.L., J.F.B. Mitchell, G.J. Boer, U. Cubasch, and V.P. Meleshko, 1992. Climate modelling, climate prediction and model validation. In: *Climate Change* 1992: *The Supplementary Report to the IPCC Scientific Assessment* (J.T. Houghton, B.A. Callander, and S.K. Varney, Eds). Cambridge University Press, 1992, pp. 97-134.

Giorgi, F., and L.O. Mearns, 1991. Approaches to the simulation of regional climate change: a review. *Rev. Geophys.*, **29**, 191-216.

Giorgi, F., M.R. Marinucci, and G. Visconti, 1992. A 2 x CO2 climate change scenario over Europe generated using a limited area model nested in a general circulation model. 2. Climate change scenario. *J. Geophys. Res.*, **97(D9)**, 10011-10028.

Gordon, H.B., P.H. Whetton, A.B. Pittock, A.M. Fowler, and M.R. Haylock, 1992. Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. *Clim. Dyn.*, **8**, 83-102

Gregory, J.M., and J.F.B. Mitchell, 1995. Simulation of daily variability of surface temperature and precipitation over Europe in the current and 2 x $CO_2$ climates using the UKMO climate model. *Q. J. R. Meteorol. Soc.*, **121**, 1451-1476.

Hall, N.M., B.J. Hoskins, P.J. Valdes, and C.A. Senior, 1994. Storm tracks in a high-resolution GCM with doubled carbon dioxide. *Q. J. R. Meteorol. Soc.*, **120**, 1209-1230

Hansen, J., M. Sato, and R. Ruedy, 1995. Long term changes of the diurnal temperature cycle: implications about mechanisms of global climate change. *Atmos. Res.*, **37**, 175-209.

Harrison, P.A., R.E. Butterfield, and T.E. Downing (Eds), 1995. *Climate Change and Agriculture in Europe. Assessment of Impacts and Adaptations*. Research Report No. 9. Environmental Change Unit, University of Oxford, UK, 414 pp.

Harvey, L.D., 1995. Warm days, hot nights. *Nature*, **377**, 15-16.

Hasselmann, K., R. Sausen, E. Maier-Reimer, and R. Voss, 1993. On the cold start problem in transient simulations with coupled atmosphere-ocean models. *Clim. Dyn.*, **9**, 53-61.

Heikinheimo, M., and A. Venäläinen, 1994. Spatial and temporal variation of global radiation in Finland. In: R. Heino (Ed.), Climate Variations in Europe. Proceedings of the European Workshop on Climate Variations held in Kirkkonummi (Majvik), Finland, 15-18 May, 1994. *Publications of the Academy of Finland 3/94*, pp. 256-262.

Heino, R., 1994. *Climate in Finland during the Period of Meteorological Observations*. Contributions No. 12, Finnish Meteorological Institute, Helsinki, 209 pp.

IPCC, 1990. *Climate Change: The IPCC Scientific Assessment*. Report of Working Group I of the Intergovernmental Panel on Climate Change (J.T. Houghton, G.T. Jenkins, and J.J. Ephraums, Eds). Cambridge University Press, Cambridge, UK, 365 pp.

IPCC, 1992. *Climate Change* 1992. *The Supplementary Report to the IPCC Scientific Assessment* (J.T. Houghton, B.A. Callander, and S.K. Varney, Eds). Cambridge University Press, Cambridge, UK, 200 pp.

IPCC, 1995. *Climate Change* 1994. *Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios* (J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell, Eds). Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 339 pp.

Hulme, M., D. Conway, P.M. Kelly, S. Subak, and T.E. Downing, 1995a. *The Impacts of Climate Change on Africa*. Stockholm Environment Institute, Stockholm, Sweden, 46 pp.

Hulme, M., S.C.B. Raper, and T.M.L. Wigley, 1995b. An integrated framework to address climate change (ESCAPE) and further development of the global and regional climate modules (MAGICC). *Energy Policy*, **23**, 347-355.

Jóhannesson, T., T. Jónsson, E. Källén, and E. Kaas, 1995. Climate change scenarios for the Nordic countries. *Clim. Res.*, **5**, 181-195.

Jones, R.G., J.M. Murphy, and M. Noguer, 1995. Simulation of climate change over Europe using a nested regional-climate model. In: Assessment of control climate, including sensitivity to location of lateral boundaries. *Q. J. R. Meteorol. Soc.*, **121**, 1413-1449.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K.P. Gallo, J. Lindseay, R.J. Charlson, and T.C. Peterson, 1993. A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteorol. Soc.*, **74**, 1007-1023.

Karl, T.R., W.-C. Wang, M.E. Schlesinger, R.W. Knight, and D. Portman, 1990. A method of relating general circulation model simulated climate to the observed local climate. Part I: Seasonal statistics. *J. Climate*, **3**, 1053-1079.

Kettunen, L., J. Mukula, V. Pohjonen, O. Rantanen, and U. Varjo, 1988. The effects of climatic variations on agriculture in Finland. In: M.L. Parry, T.R. Carter, and N.T. Konijn (Eds), *The Impact of Climatic Variations on Agriculture. Volume 1. Assessments in Cool Temperate and Cold Regions*, Kluwer, Dordrecht, The Netherlands. pp. 511-614.

McGregor, J.L., H.B. Gordon, I.G. Watterson, and M.R. Dix, 1993. *The CSIRO 9-level atmospheric general circulation model.* CSIRO Division of Atmospheric Research Technical Paper No. 26, 90 pp.

Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan, 1991. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric $CO_2$. Part I: Annual mean response. *J. Climate*, **4**, 785-818

Mitchell, J.F.B., T.C. Johns, J.M. Gregory, and S.F.B. Tett, 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. *Nature*, **376**, 501-504.

Murphy, J.M., 1995. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part I. Control climate and flux correction. *J. Climate*, **8**, 36-56.

Osborn, T.J., and T.M.L. Wigley, 1994. A simple model for estimating methane concentration and lifetime variations. *Climate Dynamics*, **9**, 181-193.

Pittock, A.B., 1993. Climate scenario development. In: A.J. Jakeman, M.B., Beck, and M.J. McAleer (Eds), *Modelling Change in Environmental Systems*. John Wiley, pp. 481-503.

Pittock, A.B., and M.J. Salinger, 1982. Toward regional scenarios for a $CO_2$-warmed Earth. *Clim. Change*, **4**, 23-40.

Posch, M., 1994. Development of a weather generator for Finland II. In: M. Kanninen, and P. Heikinheimo, (Eds), The Finnish Research Programme on Climate Change. Second Progress Report. *Publications of the Academy of Finland 1/94*, Helsinki. pp. 323-328.

Racsko, P., L. Szeidl, and M. Semenov, 1991. A serial approach to local stochastic weather models. *Ecol. Modelling*, **57**, 27-41.

Richardson, C.W., and D.A. Wright, 1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture, Agricultural Research Service, *ARS-8*, 83 pp.

Räisänen, J., 1994. A comparison of the results of seven GCM experiments in northern Europe. *Geophysica*, **30**, 3-30.

Santer, B.D., T.M.L. Wigley, M.E. Schlesinger, and J.F.B. Mitchell, 1990. Developing climate scenarios from equilibrium GCM results. *Report No. 47, Max-Planck-Institut für Meteorologie*, Hamburg, 29 pp.

Stephenson, D.B., and I.M. Held, 1993. GCM response of northern winter stationary waves and storm tracks to increasing amounts of carbon dioxide. *J. Climate*, **6**, 1859-1870 von Storch, H., J. Guddal, K.A. Iden, T. Jonson, J. Perlwitz, M. Reistad, J. de Ronde, H. Schmidt, and E. Zorita, 1993. Changing statistics of storms in the North Atlantic? *Report No. 116, Max-Planck-Institut für Meteorologie*, Hamburg, Germany, 18 pp.

Taylor, K.E., and J.E. Penner, 1994. Response of the climate system to atmospheric aerosols and greenhouse gases. *Nature*, **369**, 734-737.

TSU, 1994. *Climatic Scenarios and Socioeconomic Projections for IPCC WGII Assessment.* IPCC WGII Technical Support Unit, Washington, D.C, 12 pp. plus appendices and diskettes.

Viner, D., and M. Hulme, 1993. Construction of climate change scenarios by linking GCM and STUGE output. *Technical Note No. 2, Climate Impacts LINK Project*, Climatic Research Unit, University of East Anglia, Norwich, 20 pp.

Wigley, T.M.L., 1993. Balancing the carbon budget. Implications for projections of future carbon dioxide concentration changes. *Tellus*, **45B**, 409-425.

Wigley, T.M.L., 1994. *MAGICC User's Guide and Scientific Reference Manual.* Climatic Research Unit, University of East Anglia, Norwich, 23 pp.

Wigley, T.M.L., and S.C.B. Raper, 1992. Implications for climate and sea level of revised IPCC emission scenarios. *Nature*, **357**, 293-300.

Wigley, T.M.L., and S.C.B. Raper, 1993. Future changes in global-mean temperature and sea level. In: R.A. Warrick, E.M. Barrow, and T.M.L. Wigley (Eds), *Climate and Sea Level Change: Observations, Projections and Implications.* Cambirdge University Press, Cambridge, UK, pp. 111-133.

Wigley, T.M.L., P.D. Jones, K.R. Briffa, and G. Smith, 1990. Obtaining sub-grid-scale information from coarse-resolution general circulation model output. *J. Geophys. Res.*, **95(D2)**, 1943-1953.